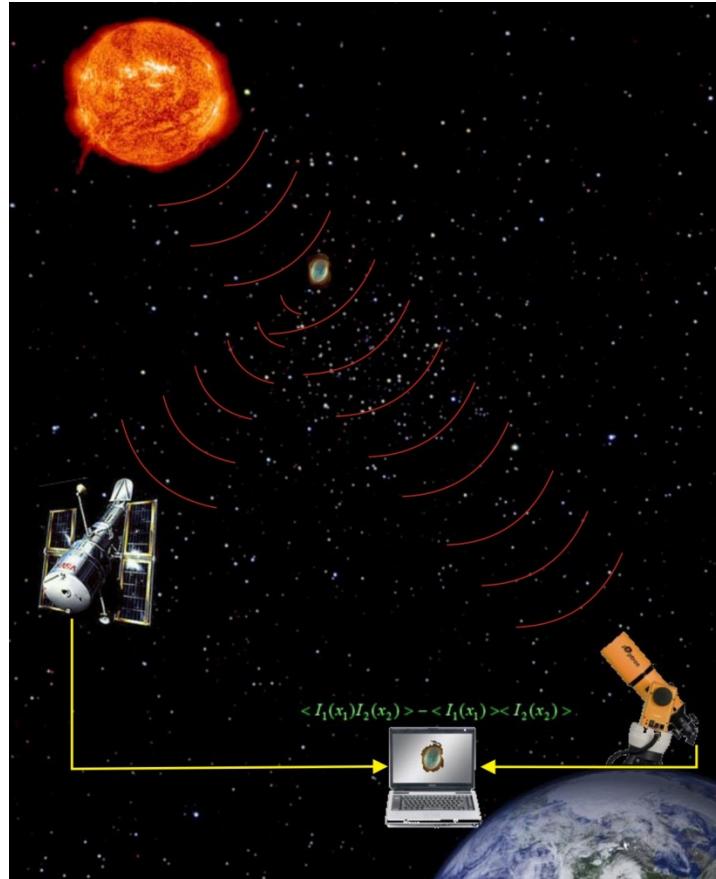


Ghost Imaging of Space Objects

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Jet Propulsion Laboratory, California Institute of Technology
Quantum Sciences and Technology group



February 6, 2014
Stanford, CA



What is Ghost Imaging, why space objects?

PHYSICAL REVIEW A

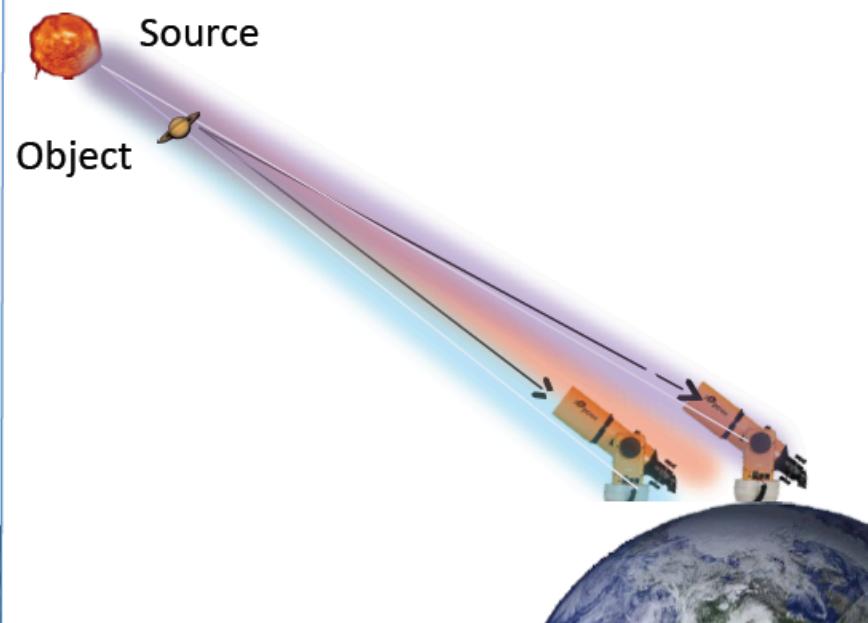
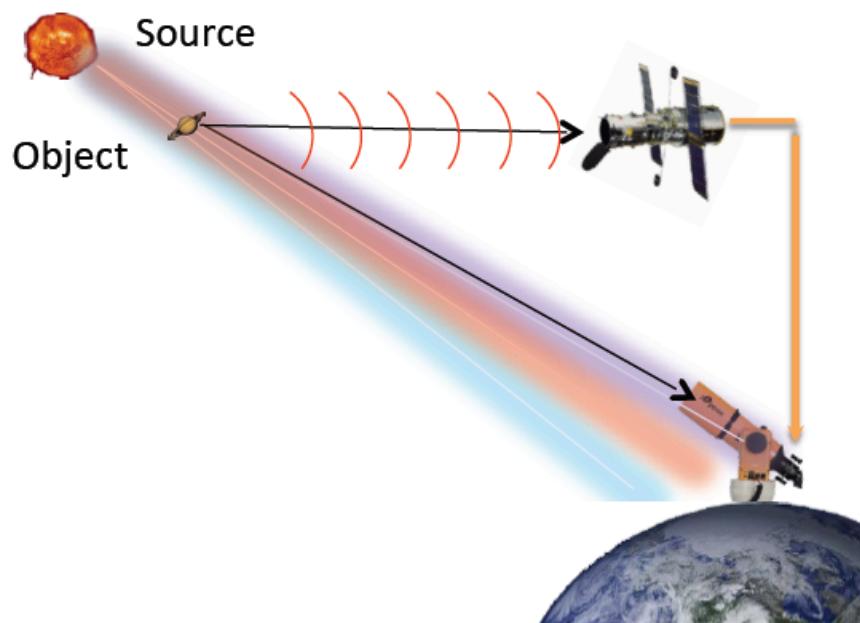
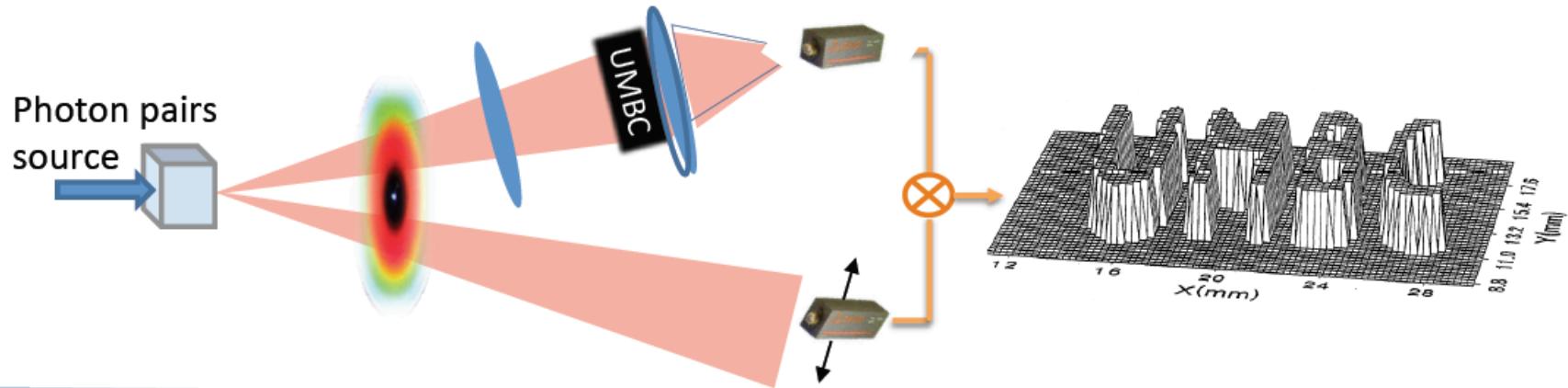
VOLUME 52, NUMBER 5

NOVEMBER 1995

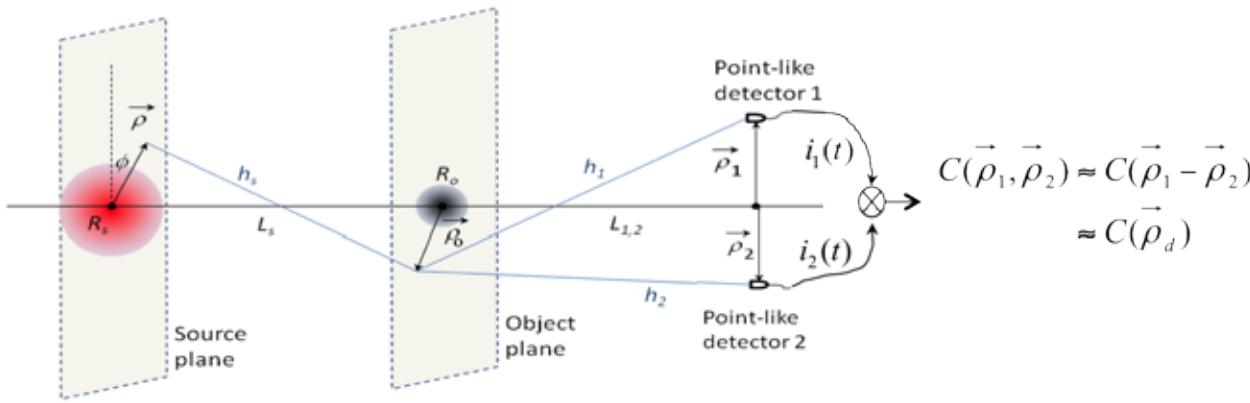
Optical imaging by means of two-photon quantum entanglement

T. B. Pittman, Y. H. Shih, D. V. Strekalov, and A. V. Sergienko

Department of Physics, University of Maryland Baltimore County, Baltimore, Maryland 21228



An object's signature encoded in the correlation function



Field propagator in paraxial approximation:

$$h_z(\vec{\rho}_1 - \vec{\rho}_2) = \frac{e^{ikZ}}{i\lambda Z} e^{ik \frac{|\vec{\rho}_1 - \vec{\rho}_2|^2}{2Z}}$$

The AC part of the correlation function can be approximated as

$$C(\rho_d) \approx C \frac{I_S^2(0)}{L^4(1 + L_S/L)^4} \left| T_S \left(\frac{k_S \rho_d}{L + L_S} \right) - \left(1 + \frac{L_S}{L} \right)^2 T_S \left((1 + \frac{L_S}{L}) \rho_O \right) \mathcal{A} \left(\frac{k_S}{L} \rho_d \right) e^{-i \frac{k_S}{L} \rho_d \cdot \rho_O} \right|^2$$

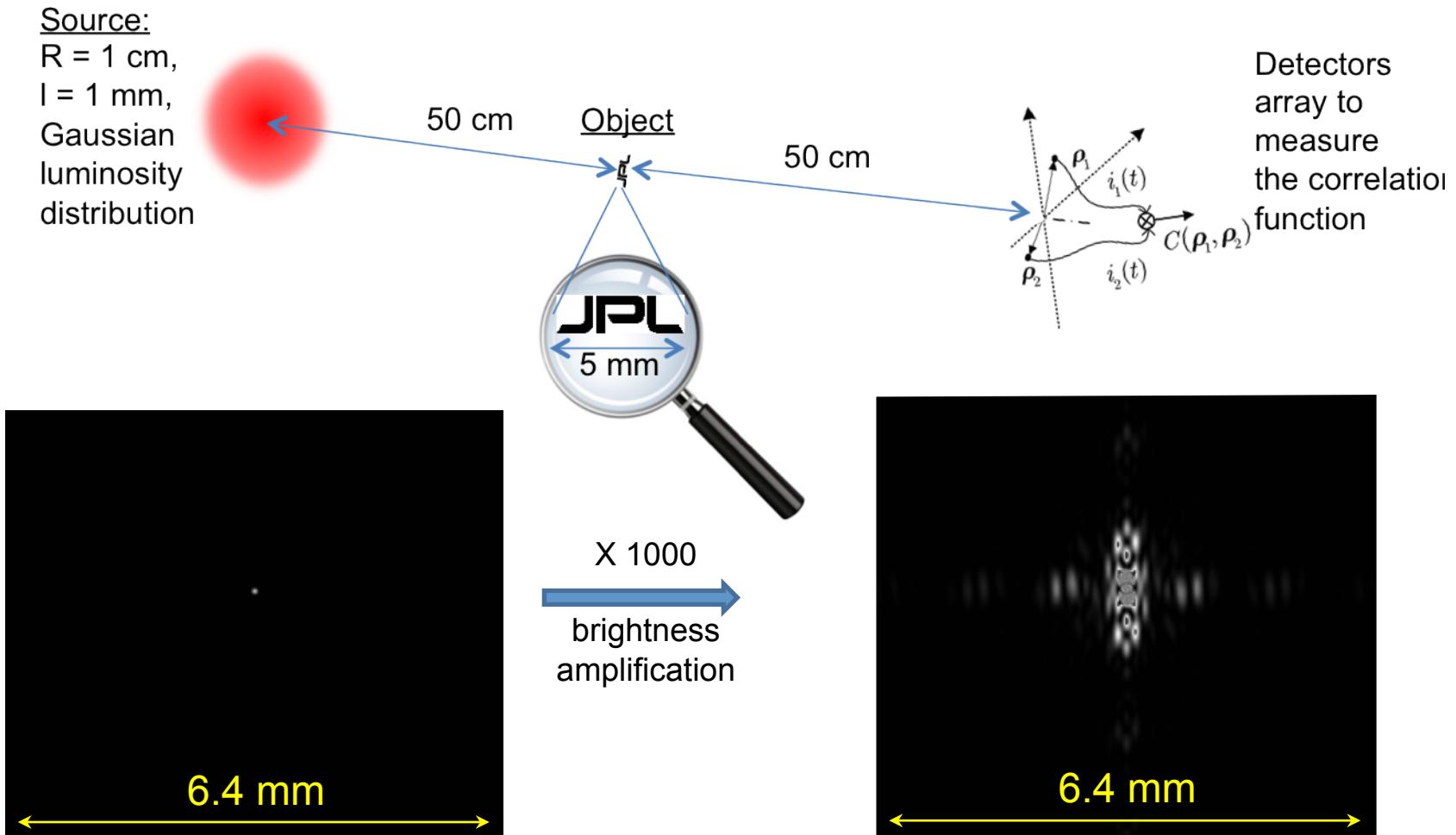
Fourier-transform of the source luminosity (van Cittert–Zernike theorem)

The source luminosity

Fourier-transform of the object opacity

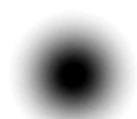
Object displacement

Image reconstruction example (numerical simulation on the lab scale)

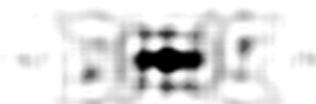


The source speckle observed in the correlation function measurement (on the left) is modified by the presence of the object. By artificially increasing its brightness (on the right) we can clearly see a structure encoding the spatial distribution of the object's opacity, which is to be recovered.
In this geometry, the object produces no tell-tale shadow!

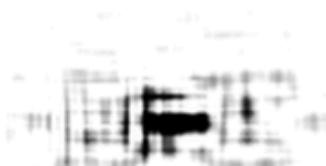
Image reconstruction by modified Gerchberg-Saxton algorithm



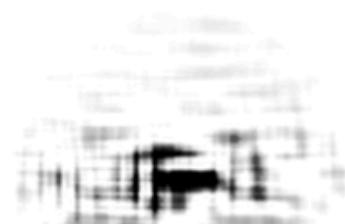
Iteration # 0 (initial guess)



1



6



12



Iteration # 24



36



48



60



Iteration # 72



84

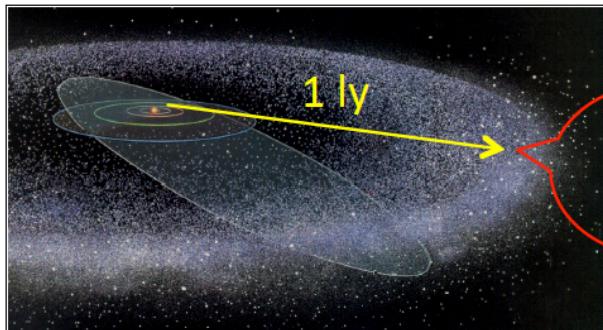


96



108

Astrophysics example: a hypothetical Earth-size planet in the Oort cloud



with two 1000 km moons

0.7 % flux reduction

8.6 ly



Sirius

6×10^{-3}
arc sec

Detectors array: 2000 x 2000, 1m-spaced, 532 nm

Detectors array are so large in order to capture the source speckle and the object/pixel speckle at the same time. Can we avoid insanely large arrays?

Astroparticle Physics 43 (2013) 331–347

Contents lists available at SciVerse ScienceDirect

Astroparticle Physics

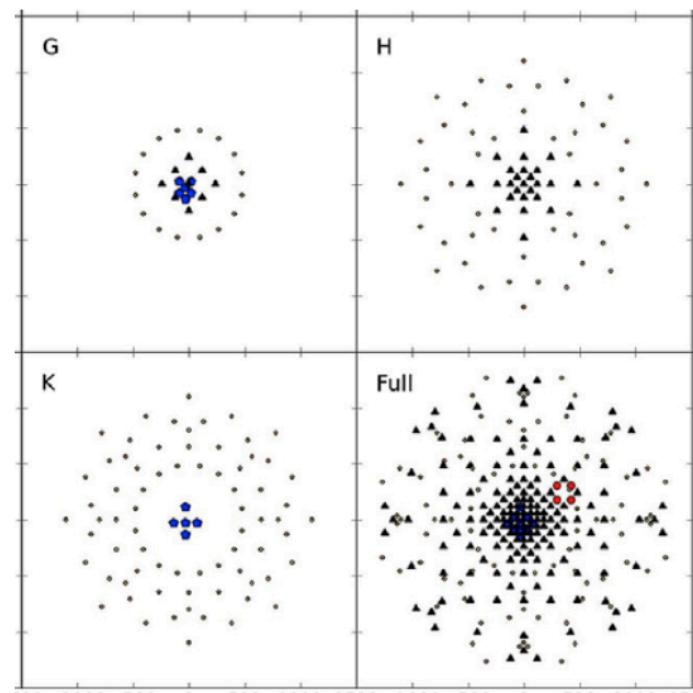


journal homepage: www.elsevier.com/locate/astropart

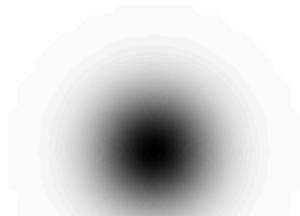


Optical intensity interferometry with the Cherenkov Telescope Array

Dainis Dravins ^{a,*}, Stephan LeBohec ^b, Hannes lensen ^{a,c,1}, Paul D. Nuñez ^b, for the CTA Consortium



The reconstruction results



Iteration # 0 (initial guess)



1



10



20



Iteration # 30



40



50



60



Iteration # 70



80

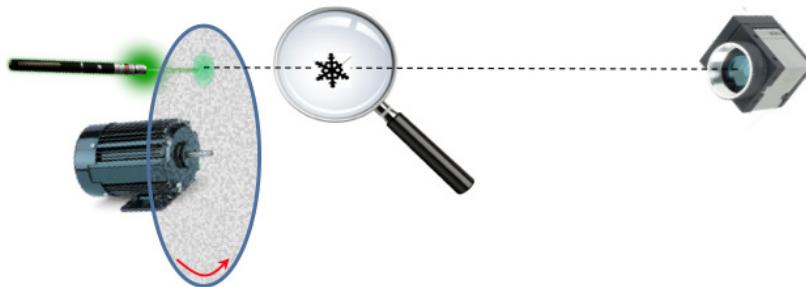


90



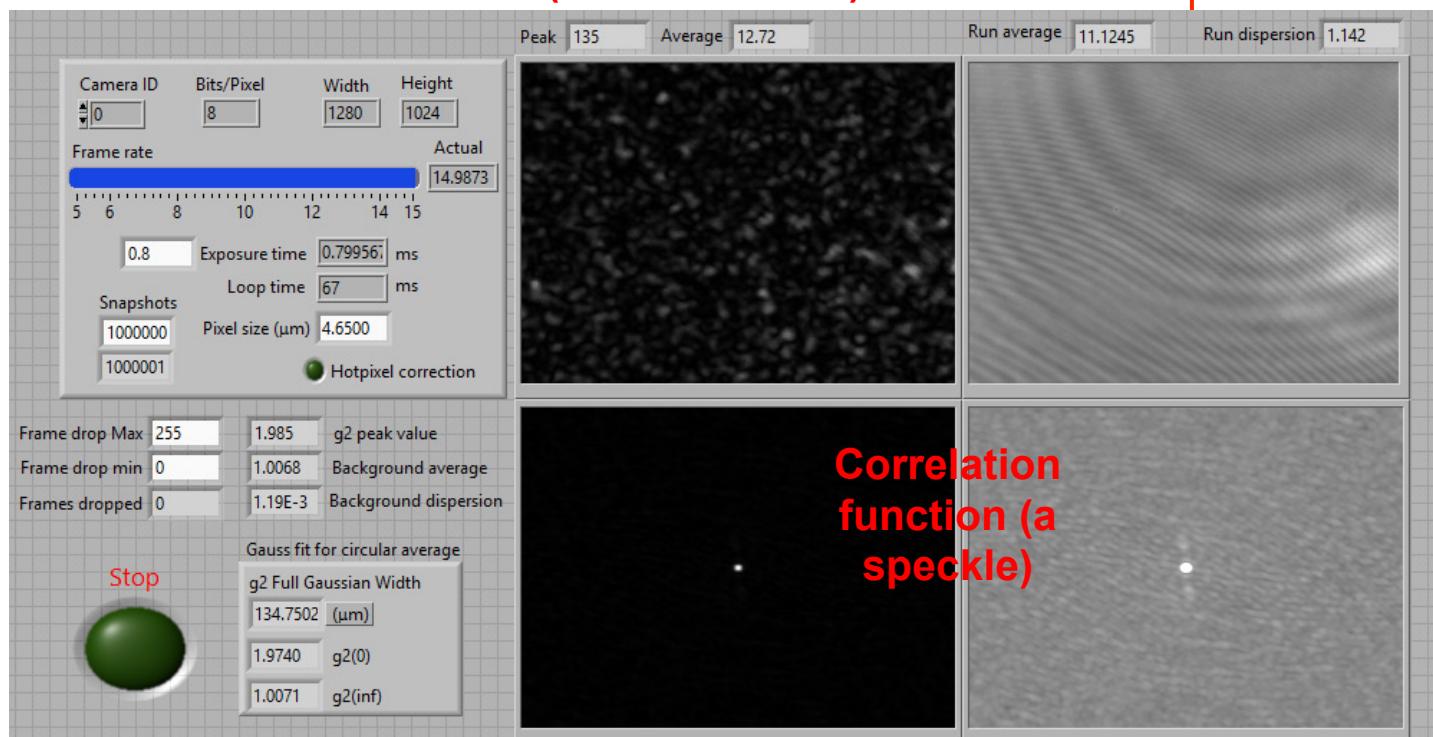
100

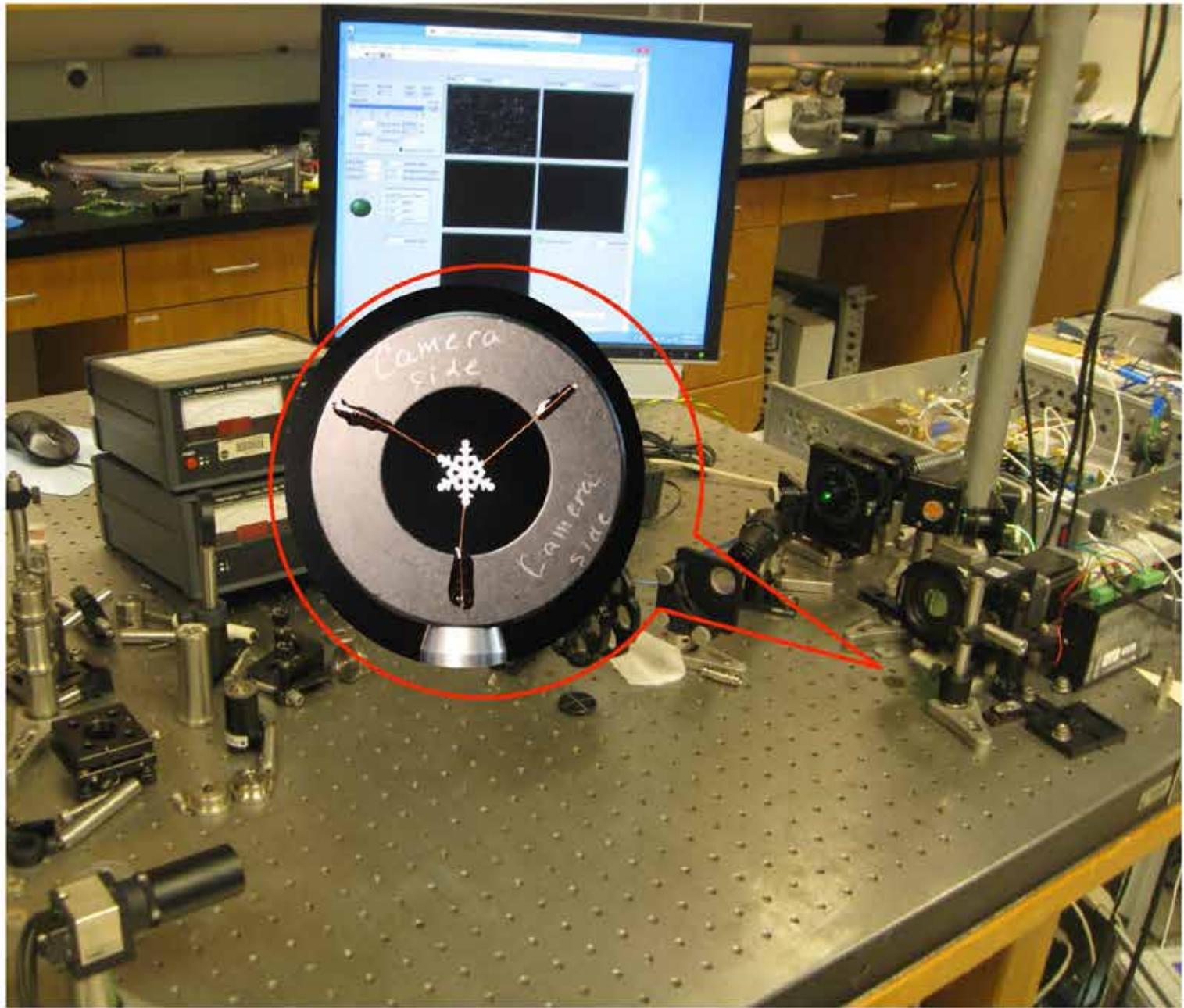
Experimental demonstration with a *pseudo-thermal* light source



Intensity distribution
(instantaneous)

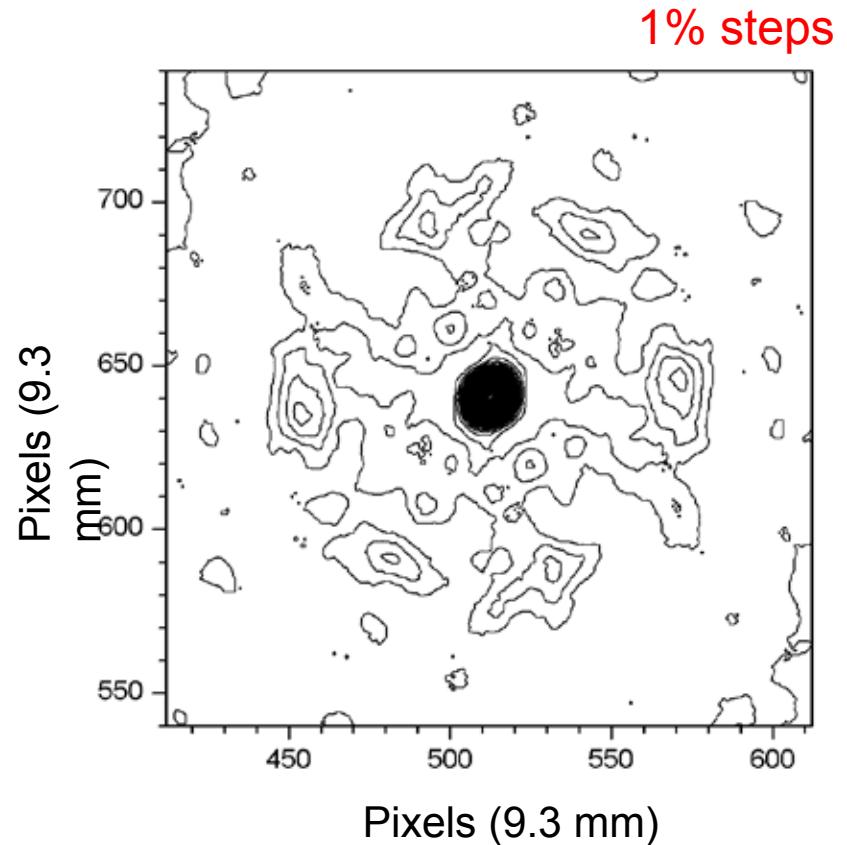
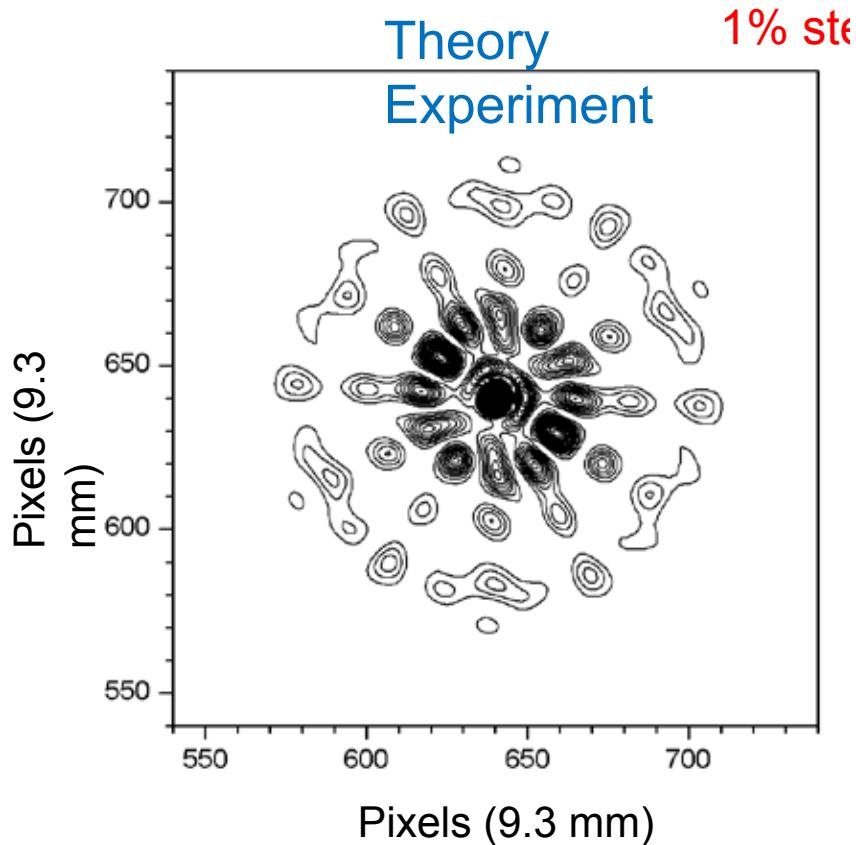
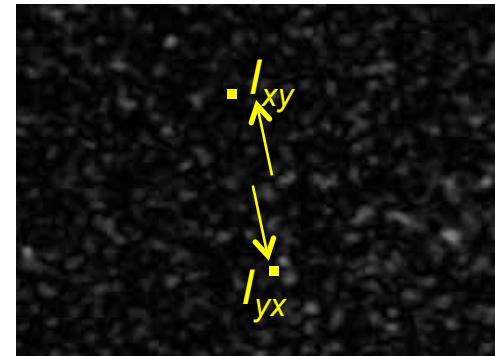
Intensity distribution
(average)





Construction of the correlation observable:

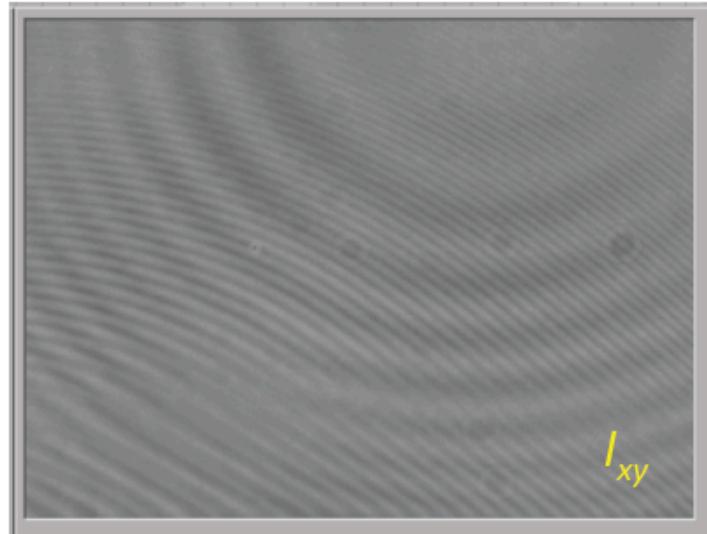
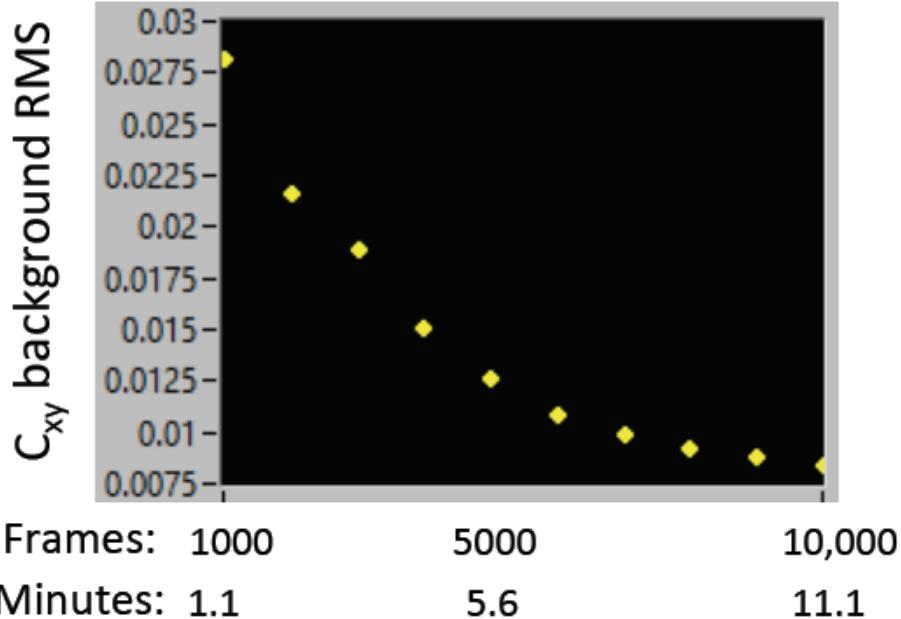
$$C_{xy} = \left\langle \frac{I_{xy}}{\sum I_{xy}} \frac{I_{yx}}{\sum I_{xy}} \right\rangle - \left\langle \frac{I_{xy}}{\sum I_{xy}} \right\rangle \left\langle \frac{I_{yx}}{\sum I_{xy}} \right\rangle$$



Well... Just wait longer!

Averaging shows unfavorable *exponential* trend:

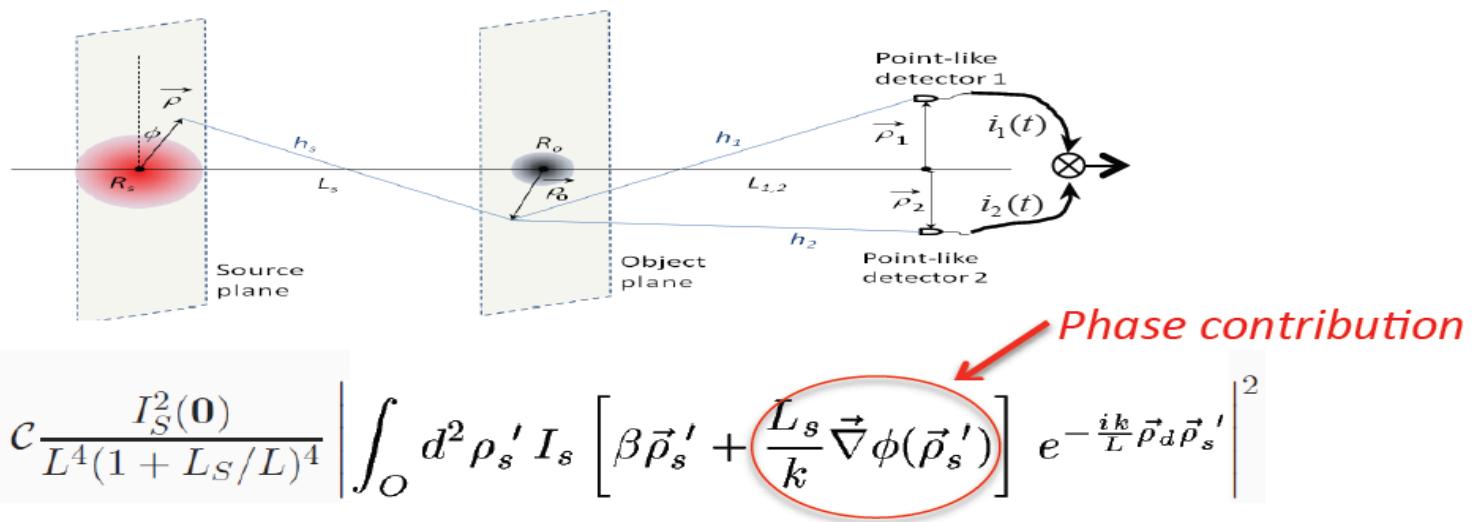
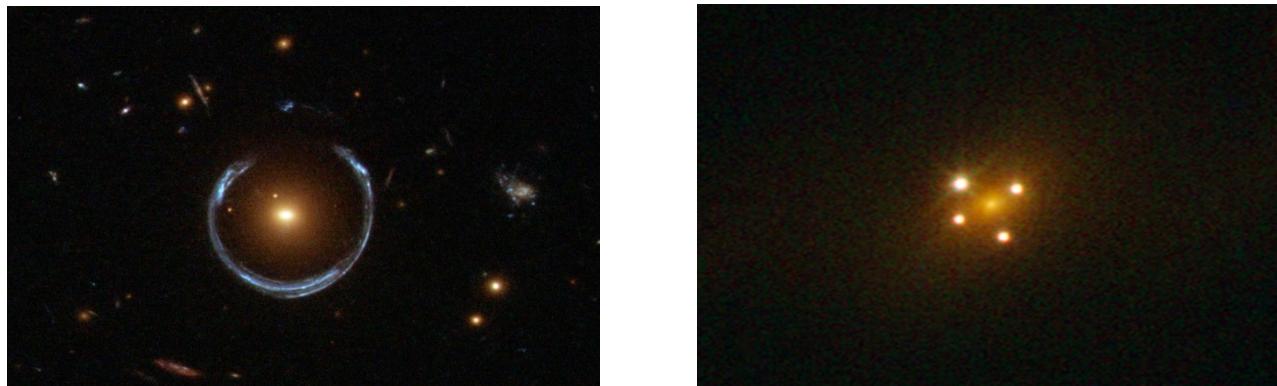
Possibly due to the fringes drift



- Suppress fringes by filling the camera with optical gel
- Thermal stabilization
- Get more averaging from each frame (off-center)

Imaging a phase object

Motivation:



Where $I_s[\dots]$ is the intensity of the source, and $\vec{\nabla} \phi$ is the gradient of phase.

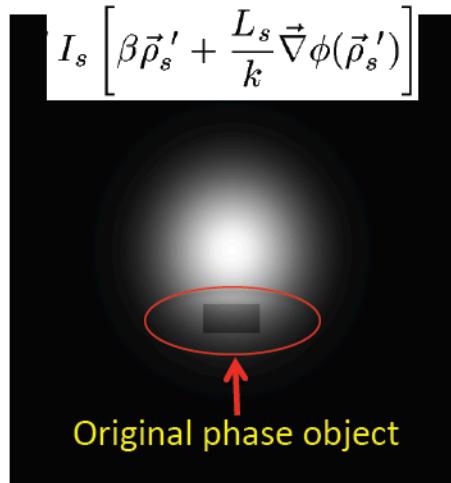
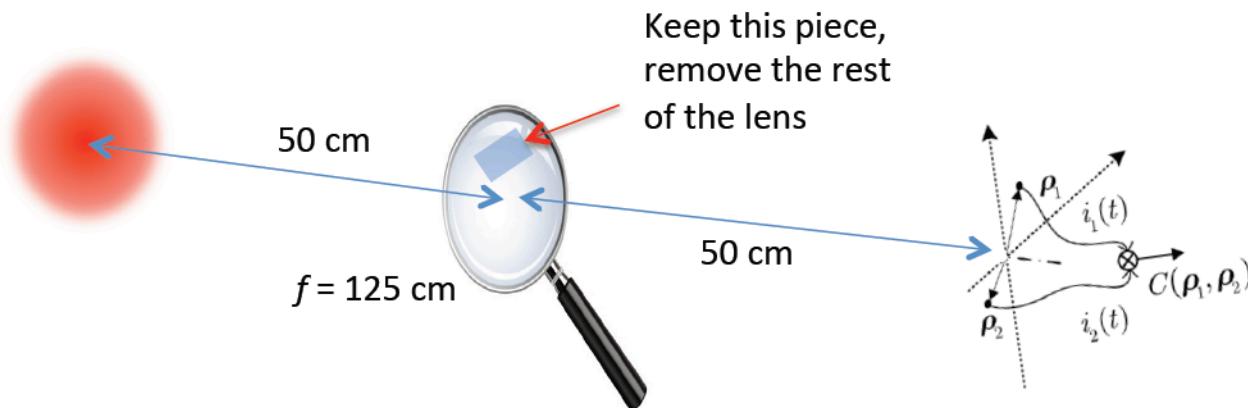
Example: a thin lens $\vec{\nabla} \phi(\vec{\rho}_s') = -\vec{\rho}_s' k/f$;

when $1/L + 1/L_s = 1/f$ $I_s[\dots] = I_s[0] = \text{const}$, and $C(\vec{\rho}_d) \propto \delta(\vec{\rho}_d)$

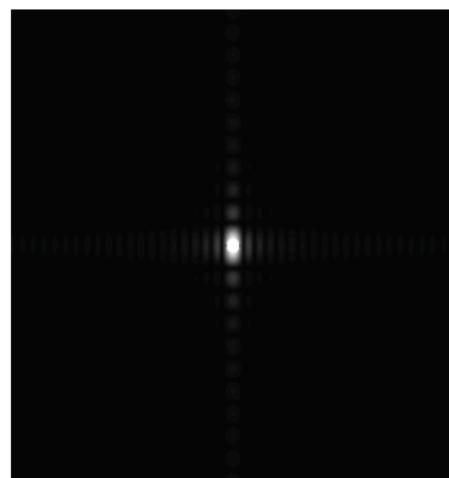
Phase object reconstruction steps:

1. Use Gerchberg-Saxon algorithm to recover the source function **with modified argument**
2. Invert $I_s[\dots]$ to recover $\vec{\nabla}\phi(\vec{p}_s')$

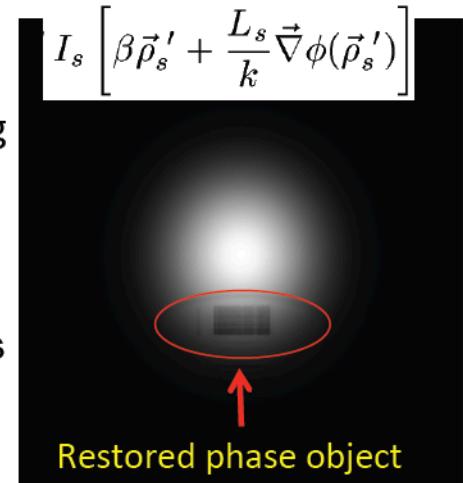
$$I_s \left[\beta \vec{p}_s' + \frac{L_s}{k} \vec{\nabla}\phi(\vec{p}_s') \right]$$



Encoding
into
correlation
function



Restoring
after
500
iterations



Summary and conclusions

Ghost Imaging may work for space exploration:

- Exoplanets
- Neutron stars
- Kuiper Belt / Oort cloud objects
- Dark matter
- Gas or dust clouds
- Gravitational lensing and microlensing

Absorbing object:

- theoretical analysis
- modified Gerchberg-Saxton algorithm
- numeric model with optical table parameters
- numeric model with astronomical parameters
- proof-of-principle optical table experiment
- proof-of-principle field experiment
- mission concept design

Other possibilities to explore:

- higher-order correlations
- transmit/reflect and reflect/reflect geometries

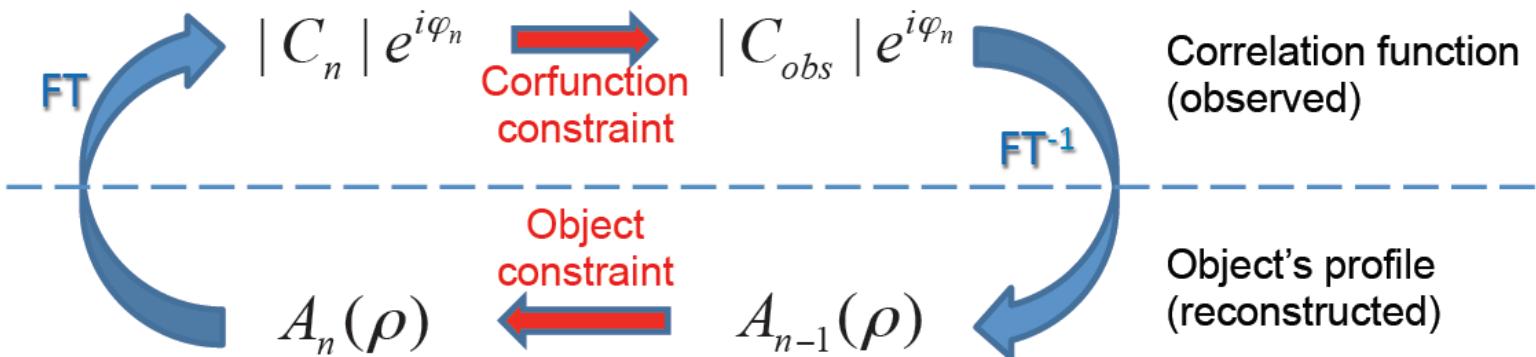
Phase object:

- theoretical analysis
- image reconstruction algorithm
- numeric models
- experiments
- mission concept design

*Outside the scope of
this NIAC project, but
we are applying to
APRA and looking for
other opportunities.*

Backup slides

Image reconstruction from incomplete Fourier Transform (Gerchberg-Saxton algorithm)



Correlation function constraint: the absolute value must match the observation

Object absorption constraint:

1. A is Real
2. $0 < A < 1^*$
3. Size limitation (not expected to be larger than...)
4. Often we know that the object is solid: $A = 0$ or $A = 1^*$
5. Using low-resolution “support” image

*) These constraints are specific to our approach